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(52) UK CL (Edition P)
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(56) Documents Cited
GB 2154744 A EP 0256659 A1 US 5280239 A

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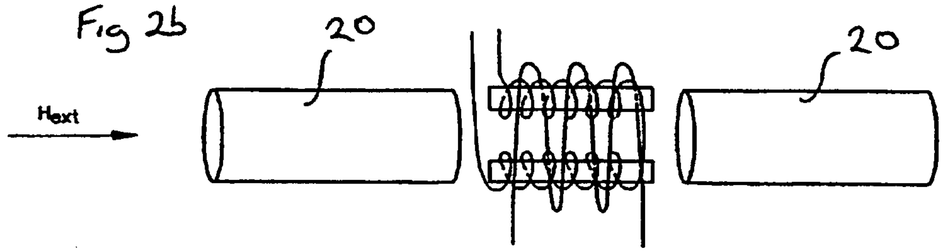
(54) Magnetometer with at least one magnetic field concentrating core

(57) A magnetometer comprises a magnetic field measuring arrangement and at least one core member 20, with a high magnetic susceptibility level, arranged to concentrate the external magnetic field H ext which passes through the said measuring arrangement. The measuring arrangement may be in the form of a flux gate magnetometer comprising sensor and feedback windings and two separate cores which are in contact with each other or a single closed path core. The flux concentrating cores 20 may be placed on either side of the measuring arrangement and may be of a loop core form and may also include demagnetising winding arrangements.

Fig 2b



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The claims were filed later than the filing date within the period prescribed by Rule 25(1) of the Patents Rules 1995

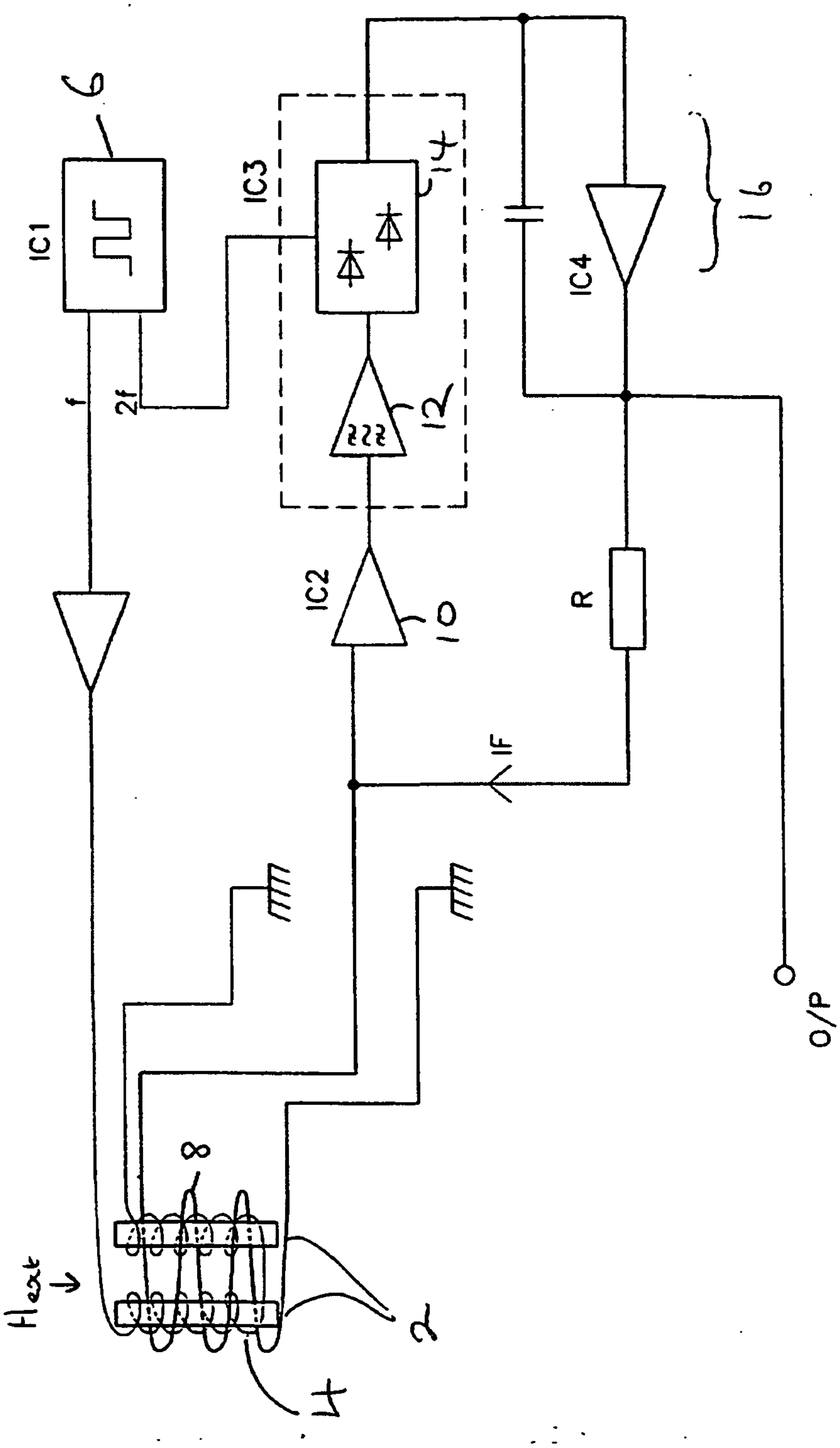


Fig 1

Fig 2a

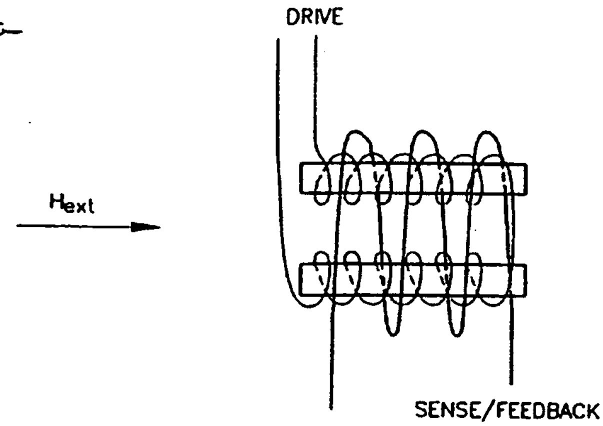


Fig 2b

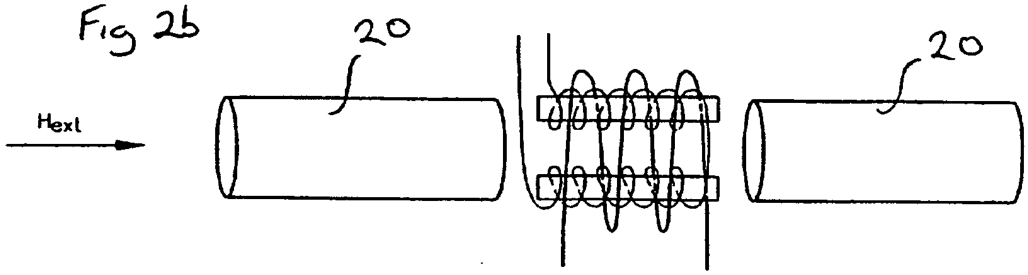


Fig 2c

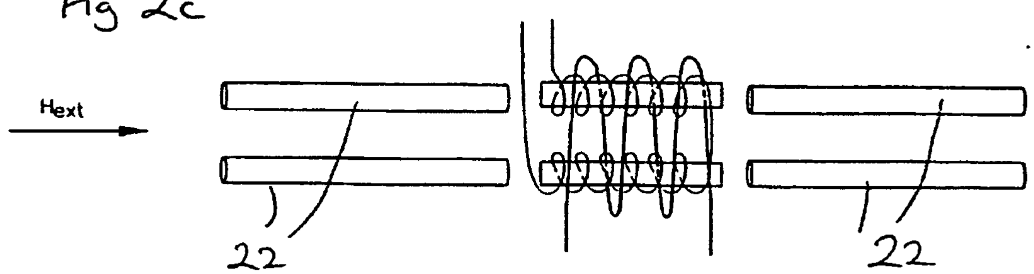


Fig 3

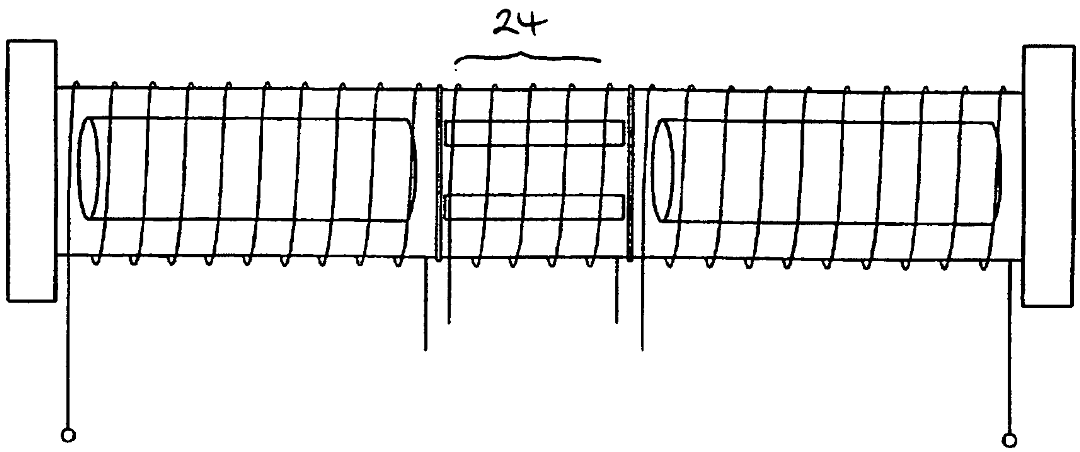


Fig 4

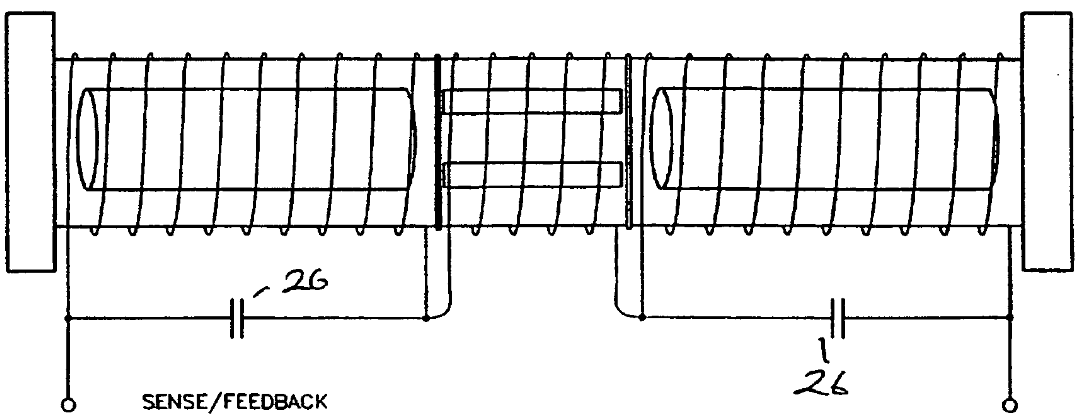


Fig 5

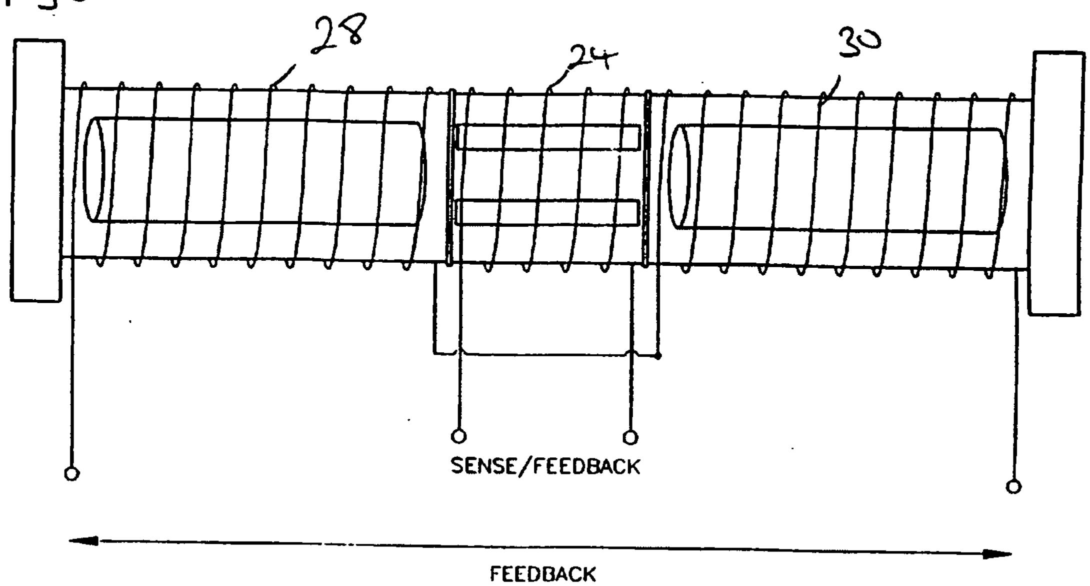

28
24
30
SENSE/FEEDBACK
FEEDBACK

Fig 6

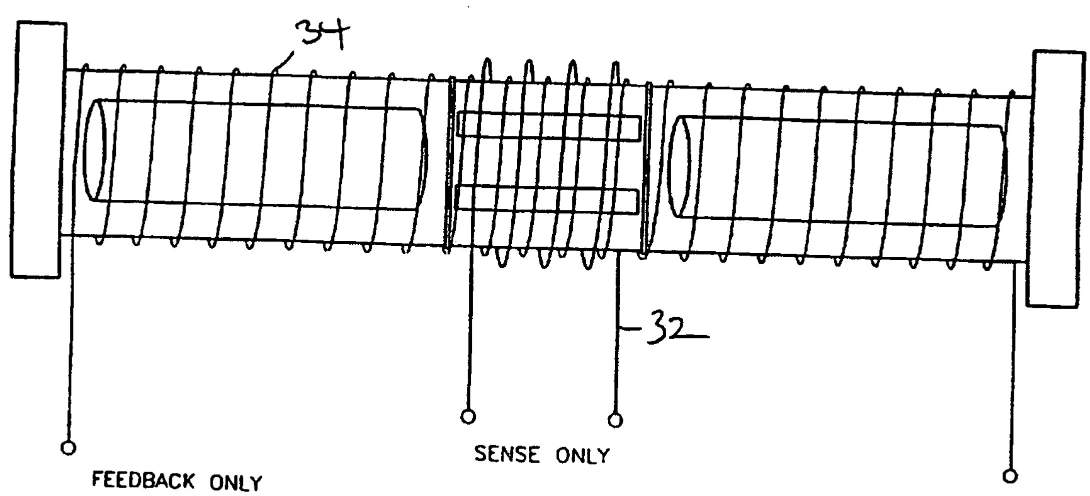

34
32
SENSE ONLY
FEEDBACK ONLY

Fig 7a

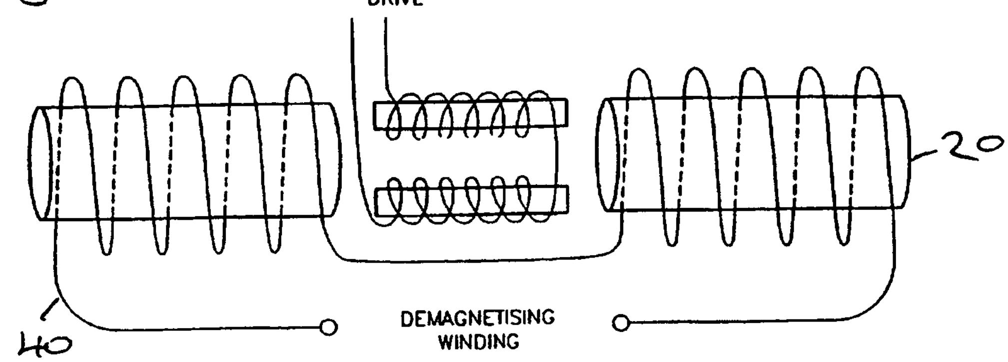
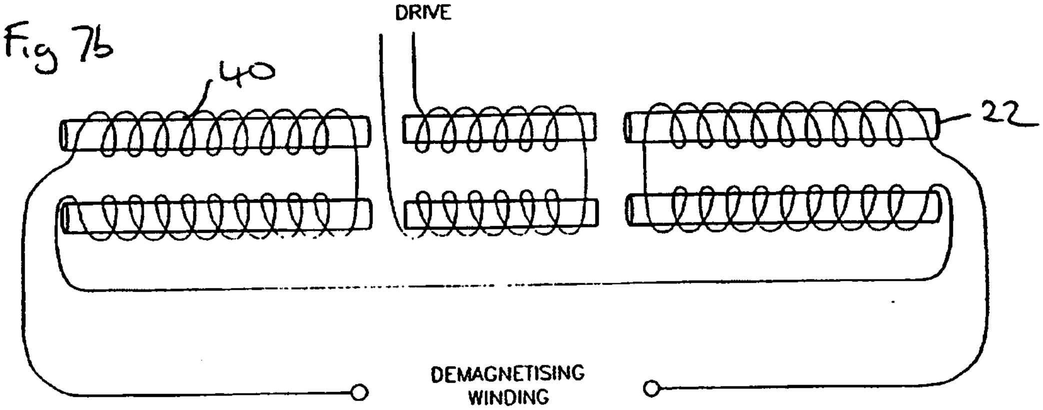
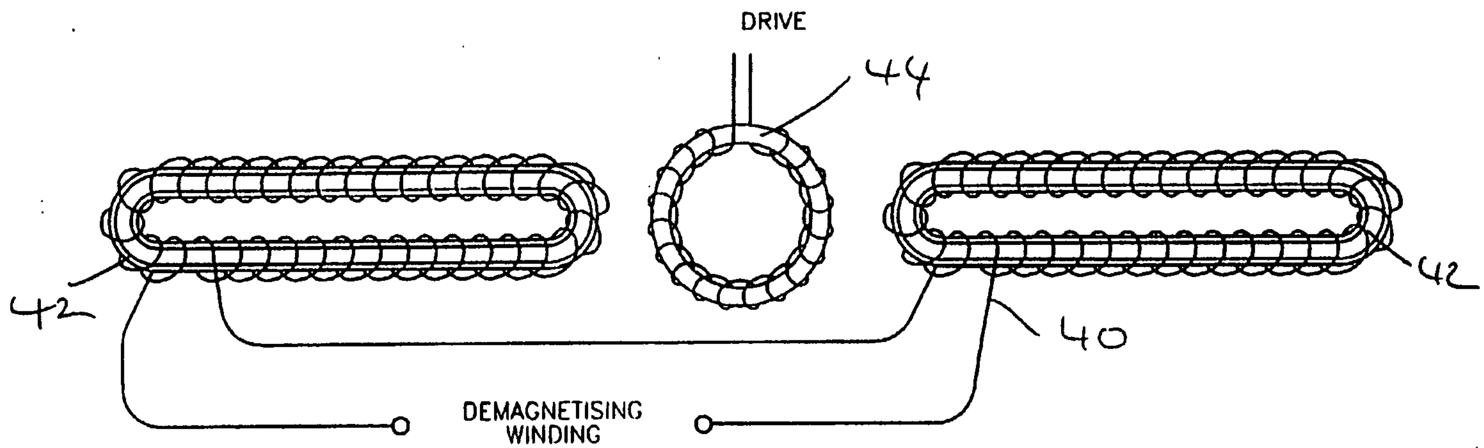


Fig 7b



SENSE WINDINGS OMITTED FOR (

Fig 8



SENSE WINDINGS OMITTED FOR CLARITY

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MAGNETOMETER

The present invention relates to a magnetometer.

Alternating magnetic fields of a reasonable frequency can be measured by magnetic field sensors consisting of coils which measure the electromagnetic force generated by the rate of change of magnetic flux linking with the circuit. However, such systems do not respond to low frequency or static magnetic fields. Such systems are also unsuitable for use on moving platforms which have rotational motion in a pass band of interest, as the rotations can generate outputs due to the rate of change of magnetic flux from the earth's static field.

It is known to measure weak magnetic fields at low frequencies by using special magnetometers, such as the fluxgate magnetometer. The general operating principle of fluxgate magnetometers is well known. However, the limiting factor on the capability of fluxgate magnetometers to resolve and measure very weak magnetic fields is the self noise of the sensor. It is known that for a well designed fluxgate magnetometer system, the self noise is dominated by the noise generated in switching the fluxgate core. Once the core exceeds a certain minimum size, further increases in the size of the core increase both the signal and the noise equally and therefore do not result in an improvement of the signal to noise ratio of the system.

Figure 1 of the accompanying drawings schematically illustrates a second harmonic

fluxgate magnetometer of a conventional design. Two linear magnetic cores 2 are over wound by drive windings 4. The windings 4 are in opposed senses such that the magnetic fields generated by the windings substantially cancel one another at positions remote from the cores 2. An oscillator 6 produces a periodic signal having a frequency F which is used to drive the cores 2 into and out of saturation twice in each cycle. Thus the in-axis field component in the plane of a sense winding 8 encircling the cores 2 is amplitude modulated by the change in permeability of the fluxgate core (the cores 2) as is goes in and out of saturation, thereby producing a signal at the second harmonic 2F of the drive frequency. An output of the sense winding 8 is provided to the input of an amplifier 10. An output of the amplifier 10 is connected to a band pass filter 12 which in turn provides a signal to a phase sensitive detector 14. Thus the signal from the sense winding 8 is amplified and band pass filtered, and then demodulated back to its base band frequency. An output of the phase sensitive detector 14 is provided to an integrator 16 which generates a feedback current IF which is used to generate a magnetic field in opposition to an external magnetic field acting on the fluxgate core. Thus, in use, the action of the magnetometer is to set up a feedback magnetic field so as to null out an external magnetic field H_{ext} within the region of the fluxgate.

According to the present invention, there is provided a magnetometer comprising a measurement cell and at least one amplification core having a magnetic susceptibility greater than zero so as to amplify an external magnetic field at the measurement cell.

It this thus possible to provide a magnetometer in which additional high permeability cores are provided around a measurement cell such that they amplify the effect of an external

field at the measurement cell. The external cores are not subjected to switching into and out of saturation and therefore do not generate switching noise.

Preferably the magnetometer is a fluxgate magnetometer with the fluxgate constituting the measurement cell.

Preferably the measurement cell comprises first and second measurement cores wound with drive windings in opposite senses. The measurement cores may be physically separate from each other or may be in contact with one another. Alternatively a single core having a "race track" or a toroid configuration may be provided. The winding is then wound in a single sense around the core.

Preferably a sense winding is wound over the measurement cell. Alternatively, individual sense windings may be provided for respective measurement cores.

Preferably the amplification cores are provided either side of the measurement cell. The cores may be separated from the measurement cell by an airgap. Single amplification cores may be used either side of the measurement cell, or small cores associated with respective ones of the measurement cores may be provided. The amplification cores may have tapered profiles enhancing the concentration of magnetic flux within the measurement cell. As a further alternative, the amplification cores may be provided as looped elements, such as a race track configuration.

Advantageously a feedback coil is included within the measuring cell so as to null the

external field occurring within the cell. The feedback coil and sense coil may be implemented as a single coil.

Preferably the amplification cores are included within the magnetic feedback system. The feedback winding can be extended to overwind the amplification cores. If a single winding is used as both the sense and feedback windings, taps may be provided along the winding so that those portions of the winding overlying the amplification cores may be shunted by a bypass capacitor. Thus the extra impedance due to the windings overlying the amplification cores is effectively short circuited at the measurement frequencies.

Alternatively, a segmented winding may be provided with those segments overlying the amplification cores being fed solely with the feedback current whereas the central portion overlying the fluxgate may be driven from a separate current source and used as a combination sense and feedback winding. The segments associated with the amplification cores can be driven individually or be series connected.

As a further alternative, separate sense and feedback windings may be provided. This allows the sense winding to be provided only in the vicinity of the fluxgate and to be optimised for its task.

The amplification cores are not continually switched into and out of saturation and consequently can become magnetised giving rise to offset and possibly drift with time and temperature. To overcome this, the amplification cores may be demagnetised, either via the feedback winding or via separate demagnetising windings.

The present invention will further be described, by way of example, with reference to the accompany drawings, in which;

Figure 1 is a schematic diagram of a known fluxgate magnetometer;

Figure 2a schematically illustrates the fluxgate core of the magnetometer shown in figure 1;

Figures 2b and 2c schematically illustrate the modification of the core by the inclusion of external amplifying cores;

Figure 3 schematically illustrates an embodiment of the present invention having a segmented sense and feedback winding;

Figure 4 schematically illustrates an embodiment of the present invention having a segmented sense and feedback winding with bypass capacitors;

Figure 5 schematically illustrates an embodiment in which the winding overlying the fluxgate is used for sense and feedback whereas the windings overlying the amplifying cores are used only for feedback;

Figure 6 schematically illustrates an embodiment having an additional sense winding;

Figures 7a and 7b schematically illustrating embodiments including demagnetising

windings; and

Figure 8 schematically illustrates an embodiment having race track amplification cores.

Figure 2a illustrates the fluxgate arrangement shown in Figure 1 in greater detail. As indicated, the fluxgate is arranged to measure magnetic fields H_{ext} acting along the direction of the axis of the cores. The applicant has realised that it is possible to enhance the sensitivity of the fluxgate without increasing the switching noise by the provision of external amplification cores 20 and 22, as illustrated in Figures 2b and 2c. The cores 20 illustrated in Figure 2b have a diameter substantially equal to the width of the fluxgate, whereas the cores 22 illustrated in Figure 2c have substantially the same diameter as the sense cores in the fluxgate and are alined therewith. The amplification cores 20 and 22 are made of materials exhibiting large magnetic permeabilities μ. The magnetic permeability μ is the ratio of the magnetic induction in a sample to the magnetic field producing it. Thus in the presence of an external magnetic field of strength H_{ext} the magnetic field B at the fluxgate will be given by

$$B = \mu_o (H_{ext} + M)$$

where $M = H_{ext}\chi$ (where χ is the magnetic susceptibility of a material)

Thus the amplification cores effectively provide an induced field H_{ext}' which adds to H_{ext} and increases the field seen by the fluxgate assembly. As the amplification cores are not driven, they do not suffer from the switching noise induced in the fluxgate cores and

consequently provide noise free amplification of the external field. The overall resolution of the magnetometer is thus improved and the equivalent self noise of the fluxgate in magnetic units is reduced after recalibration of the device to take account of the increased sensitivity.

The known fluxgate magnetometer as described with reference to Figure 1, has low hysteresis, non-linearity and gain drift due to the application of magnetic feedback to null the field being measured. The arrangements shown in Figures 2b and 2c degrade these parameters as the additional high permeability cores are outside the magnetic feedback loop. In order to overcome these disadvantages, the magnetic feedback loop is extended to incorporate the additional cores 20 and 22.

A simple approach to extend the feedback loop would simply be to extend the spatial extent of the sense/feedback winding such that it covers the complete assembly, ie. cores 20 as well as the fluxgate. The disadvantage of this approach is that impedance of the winding is increased without any corresponding increase in the magnitude of the sense signal. This has the effect of reducing the signal to noise ratio. In order to overcome this problem, the combined sense/feedback winding is formed in segments with one of the segments 24 covering the area of the fluxgate assembly only. The segments can then be connected in series with bypass capacitors 26 shunting the windings overlying the amplification cores such that DC current flows through the entirety of the windings but that AC current at the measurement frequencies effectively bypasses the outer most segments and only flows through segment 24. Alternatively, the outer most segments 28 and 30 can be connected in series and act only as feedback windings whereas the inner segment 24

acts as a combined sense and feedback winding. A current mirror (not shown) may be included to ensure that the current flowing in the windings 28 and 30 accurately matches the feedback current set up in the winding 24. As a further alternative, separate sense and feedback windings may be provided with the sense winding 32 being provided only in the vicinity of the fluxgate assembly whereas the feedback winding 34 covers both the amplification cores and the fluxgate assembly, as shown in Figure 6.

One of the features of the conventional magnetometer design is that it has low offset as the fluxgate cores are automatically demagnetised by being continuously switched into and out of saturation by the drive waveform. The additional amplification cores are not switched and consequently may become magnetised with time. Once magnetised, a large offset is produced and this magnetisation is likely to drift with time and temperature. This drift degrades the resolution of the magnetometer at low frequencies. This problem can be resolved by demagnetising the additional cores. A demagnetising winding 40 is provided around the additional amplification cores 20 and 22 as shown in Figures 7a and 7b, respectively. The demagnetising windings 40 are energised with a low frequency demagnetising current which is decayed to zero over a period of several seconds each time the magnetometer is switched on. The best results are obtained when the demagnetising field is applied in conjunction with the magnetic feedback. At switch on, the feedback is operated to null the axial component of the earth's static magnetic field, and then the demagnetising field demagnetises the additional high permeability cores in the resulting field which is close to zero. Once demagnetised, the magnetic feedback maintains the additional high permeability cores in substantially a null field, thereby preventing the cores from becoming remagnetised.

Although the invention so far has been described with reference to linear core second harmonic fluxgate magnetometers, it is equally applicable to other types of fluxgate magnetometers, and to different geometries of fluxgate and high permeability cores. Figure 8 schematically illustrates a fluxgate magnetometer having race track configuration amplification cores 42 and toroidal sense core 44. However, the principle of operation of this embodiment is as hereinbefore described.

In tests the noise performance of a commercially available magnetometer core having an external diameter 29mm was improved from an effective noise figure of 24pT peak to peak, to approximately 6pT peak to peak by the provision of four race-track cores each having a length of 155mm and a width of 29mm. This gives a reduction in noise power of approximately sixteen times.

It is thus possible to utilise external cores to provide noise free amplification of the external magnetic field thereby improving the resolution and signal to noise ratio of a magnetometer.

<u>**CLAIMS**</u>

1. A magnetometer comprising a measurement cell and at least one amplification core having a magnetic susceptibility greater that zero so as to amplify an external magnetic field at the measurement cell.

2. A magnetometer as claimed in claim 1, in which the magnetometer is a flux gate magnetometer with the flux gate constituting the measurement cell.

3. A magnetometer as claimed in claim 1 or 2, in which the measurement cell comprises first and second measurement cores wound with drive windings in opposite senses.

4. A magnetometer as claimed in claim 3, in which the measurement cores are separate from each other.

5. A magnetometer as claimed in claim 3, in which the measurement cores are in contact with one another.

6. A magnetometer as claimed in any one of claims 1 to 3, comprising a single measurement core forming a closed path.

7. A magnetometer as claimed in any one of the preceding claims, further comprising a sense winding wound over the measurement cell.

8. A magnetometer as claimed in claim 3, further comprising individual sense windings wound over respective measurement cores.

9. A magnetometer as claimed in any one of the preceding claims, in which amplification cores are provided either side of the measurement cell.

10. A magnetometer as claimed in claim 9, in which single amplification cores may be used either side of the measurement cell, or small cores associated with respective ones of the measurement cores may be provided.

11. A magnetometer as claimed in claim 10, in which the amplification cores have tapered profiles enhancing the concentration of magnetic flux within the measurement cell.

12. A magnetometer as claimed in claim 10, in which the amplification cores may be provided as looped elements, such as a race track configuration.

13. A magnetometer as claimed in any preceding claim, in which a feedback coil is included within the measuring cell so as to null the external field occurring within the cell.

14. A magnetometer as claimed in claim 13, in which the feedback coil and sense coil may be implemented as a single coil.

15. A magnetometer as claimed in claim 13, in which the amplification cores are included within the magnetic feedback system.

16. A magnetometer as claimed in any one of claims 13 to 15 in which the feedback winding is extended to overwind the amplification cores.

17. A magnetometer as claimed in claim 14, in which taps are provided along the winding so that those portions of the winding overlying the amplification cores are shunted by a bypass capacitor.

18. A magnetometer as claimed in claim 13, in which a segmented winding is provided with those segments overlying the amplification cores being fed solely with the feedback current whereas the central portion overlying the flux gate is driven from a separate current source and used as a combination sense and feedback winding.

19. A magnetometer as claimed in any one of the preceding claims, in which the amplification cores may be demagnetised, either via the feedback winding or via separate demagnetising windings.

The Patent Office

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Application No:	GB 9616304.3	**Examiner:**	J. A. Watt
Claims searched:	1 - 19	**Date of search:**	25 September 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1U (UR3300, UR3302, UR33025, UR3304)

Int Cl (Ed.6): G01R 33/00, 33/02, 33/025, 33/04

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	GB 2154744 A	(STC) see figures 3 - 5 and lines 7 - 21 of column 1	1 at least
X	EP 0256659 A1	(SECURITY TAG SYSTEMS) see figure 5 and lines 1 - 7	1 at least
X	US 5280239	(A. K. VLADIMIR) see figures 2 & 4 - 8 and lines 44 - 62 of column 2	1 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		